Guidelines for *Positioning* Using GPS

DRAFT 7, June 10, 2001

SSMC3-8854, (301) 713-3194, Joe.Evjen@noaa.gov

1. INTRODUCTION

2. STANDARDS OF ACCURACY

3. GENERAL GUIDELINES

4. DETAILED GUIDELINES

5. APPENDICES

Notes for Reviewers:

DOCUMENT AVAILABILITY:

VIA INTERNET: In PDF & WPD formats, at http://www.ngs.noaa.gov/ADVISORS/FBN/GPSmanual/
VIA E-MAIL: Upon request, from Joe.Evjen@noaa.gov

REVIEW INSTRUCTIONS:

Critiques in any written format are welcome (via digital or paper markup or e-mail). Your suggestions will be incorporated into the next release. When convenient, subtle changes will be shown using the new version redline method.

Please be brutal and thorough! Review iterations will be limited to ensure timely release of this document. Please make specific suggestions on changes to be made. If there are any major revisions to the document format, I want them to occur in early drafts! Please pay special attention to the document's readability; note any sections which are not clear or confusing. Don't spare the ink!

REVIEW NOTES:

- **DRAFT sections are highlighted in yellow**. Details in these sections are pending. Any information you have to help complete these sections is appreciated.

- *Questionable or significantly new statements are written in* ***italics, ??, or XXX***. Your comment on these sections is appreciated.

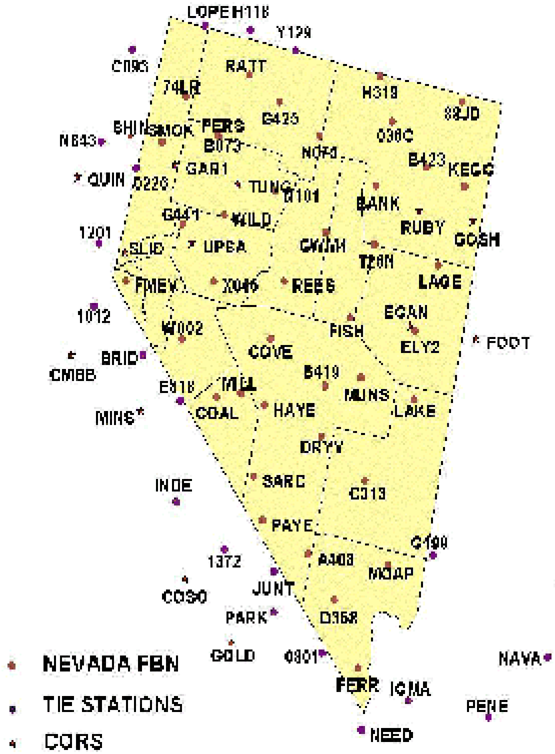
- Miscellaneous review notes are written at the bottom of the pages. These notes will not be a part of the final document.

- THANK YOU for your efforts in developing this document!

1. INTRODUCTION

1.1 PREFACE

Many spatial activities, such as navigation, mapping, and surveying, use geographic coordinates to describe the position of objects. Whenever two activities share a common coordinate system, their data can be more readily compared and exchanged. For this reason, Federal and state mapping products are referenced to two standard coordinate systems: the North American Datum of 1983 (NAD 83) for horizontal positions and ellipsoid heights, and the North American Vertical Datum of 1988 (NAVD 88) for orthometric heights. Surveys are referenced to these datums through measurements to control points of the National Spatial Reference System (NSRS).



The NSRS is a set of geographic point attributes which provides a consistent framework to coordinate all spatial activities. The NSRS includes a nationwide network of Continuously Operating Reference Stations (National CORS), statewide Federal & Community Base Networks (FBN/CBN), regional User Densification Networks (UDN), and other historic vertical and horizontal control.

The purpose of these guidelines is to describe recommended procedures for the establishment and densification of these control networks using the Global Positioning System (GPS). This document updates the 1989 Federal Geodetic Control Subcommittee (FGCS) document “DRAFT Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques”[1] and the 1998 NOAA Technical Memorandum “NGS-58, Guidelines for Establishing GPS-Derived Ellipsoid Heights”[2].

In accordance with new Federal positioning standards [3], these guidelines rely heavily on the use of statistical analyses to determine the accuracy of a survey. For this approach to be valid, a determined effort must be made to detect and minimize systematic errors (biases) and eliminate blunders. Fundamental to this effort is the use of careful survey procedures, redundancy of measurements, and thorough documentation to describe and verify results.

The procedures described below were derived from National Geodetic Survey (NGS) experience with state-wide and regional network surveys and equipment testing. Note that these guidelines describe only a few of the many methods available for performing GPS surveys. Other methods, including code, absolute, kinematic and real-time GPS measurements, or variations of equipment, network design, or office procedures, may yield comparable results. Future improvements in measurement or processing technologies may yield higher accuracies. Users are encouraged to explore new methodologies using the validation survey concepts explained in Appendix 10.5.

1.2 SURVEYING WITH GPS

All GPS surveying techniques are based upon ~~*interferometric*~~ observations of radio signals from a network of orbiting satellites. These signals are processed to compute station positions by trilateration: the positions of the satellites and computed ranges are used to determine the antenna position. These positions are normally computed in an earth-centered Cartesian coordinate (x,y,z) system, which can be converted to geodetic curvilinear coordinates (latitude, longitude, and ellipsoidal height). With the addition of a geoid height model, orthometric heights can be computed.

The accuracy of a GPS survey is dependent upon many complex, interactive factors, including:

C Observation technique used, e.g., static vs. kinematic, code vs. phase, etc.
C Amount and quality of data acquired
C GPS signal strength and continuity
C Ionospheric and tropospheric conditions
C Station site stability, obstructions, and multipath
C Satellite orbit used, e.g., predicted vs. precise orbits
C Satellite geometry, described by the Dilution of Precision (DOP)
C Network design, e.g., base line length and orientation
C Processing methods used, e.g., double vs. triple differencing, etc.

Error sources in a GPS survey include the following:

C	Reference position errors	- coordinate, monument stability, crustal motion
C	Antenna position errors	- equipment setup, phase center variation and offsets
C	Satellite position errors	- orbit ephemeris errors
C	Timing errors	- satellite or receiver clock errors
C	Signal path errors	- atmospheric delay and refraction, multipath
C	Signal recording errors	- receiver noise, cycle-slips
C	Human errors	- field or office blunders
C	Computing errors	- processing and statistical modeling errors

All errors should be identified and minimized by statistical testing and careful operational procedures, including the following:

C Repetition of measurements under independent conditions
C Redundant ties to multiple, high-accuracy control stations
C Geodetic-grade instrumentation, field procedures, and office procedures
C Processing with the most accurate station coordinates, satellite ephemerides, and atmospheric and antenna models available

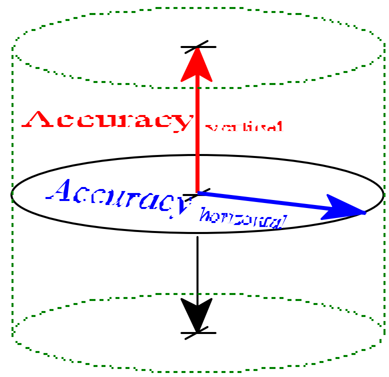
Be aware that these procedures cannot disclose all problems.

2. STANDARDS OF ACCURACY FOR GPS SURVEYS

2.1 STANDARDS OF ACCURACY FOR GEOSPATIAL POSITIONING

Quoted verbatim from the Federal Geographic Data Committee FGDC-STD-007.1-1998, Geospatial Positioning Accuracy Standards Part 1: Reporting Methodology:

Accuracy Standard *All spatial data activities should develop a classification scheme following the standard given below. The standard for reporting positional accuracy is defined for horizontal and/or vertical coordinates, depending on the characteristics of the data sets.*



Horizontal*: The reporting standard in the horizontal component is the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95-percent of the time.*

Vertical*: The reporting standard in the vertical component is a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of that linear uncertainty value 95-percent of the time. The reporting accuracy standard should be defined in metric (International System of Units, SI) units. However, accuracy will be reported in English (inch-pound) units where the point coordinates or elevations are reported in English units.*

The new standards support both local and network accuracies:

local accuracy *- The local accuracy of a control point is a value that represents the uncertainty in the coordinates of the control point relative to the coordinates of other directly connected, adjacent control points at the 95-percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.*

network accuracy *- The network accuracy of a control point is a value that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95-percent confidence level. For NSRS network accuracy classification, the datum is considered to be best expressed by the geodetic values at the Continuously Operating Reference Stations (CORS) supported by NGS. By this definition, the local and network accuracy values at CORS sites are considered to be infinitesimal, i.e., to approach zero.*

The accuracy of classical triangulation network surveys was described by a proportional standard, e.g., 1:10,000, which reflected the distance-dependant nature of terrestrial surveying error. The accuracy of GPS and photogrammetric surveys, being less distance dependant, used different accuracy standards. This use of multiple standards created difficulty in comparing the accuracy of coordinate values obtained by different survey methods.

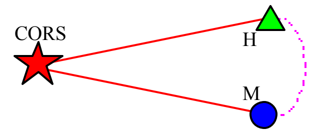
In recognition of these difficulties, the Federal Geographic Data Committee (FGDC) has changed its methodology for reporting the accuracy of horizontal and vertical coordinate values. The new reporting standard is defined by 95% confidence intervals; a circle for horizontal uncertainty and a linear value for vertical uncertainty.

Local accuracy is best adapted to check relations between nearby control points, for example, a surveyor checking closure between two NSRS points is most interested in a local accuracy measure. On the other hand, someone constructing a GIS will often need some type of positional tolerance associated with a set of coordinates. Network accuracy measures how well coordinates approach an ideal, error-free datum. For more information on local and network accuracies, consult the FGDC publication "Geospatial Positioning Accuracy Standards"[3].

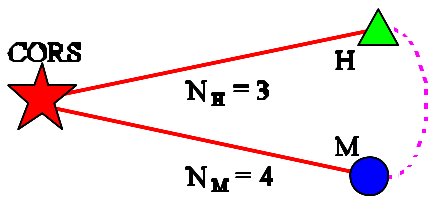
2.2 NETWORK AND LOCAL ACCURACY RELATIONSHIPS

Network and local accuracies are fundamentally similar concepts; with local accuracy describing the positional accuracy between two points, and network accuracy describing the positional accuracy between a point and the CORS network. Used together, network and local accuracy classifications are helpful in estimating accuracies between points not directly measured, or in comparing positions determined from two separate surveys. Consider the following examples:

1) **LOCAL TIE MISSING:** If adjacent stations are positioned independently, the local accuracy between the stations can be computed from each point's network accuracy.

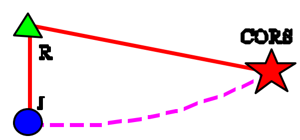


TO ESTIMATE LOCAL ACCURACY, L_{HM}:
Let N_H = The network accuracy of station "HATFIELD", and
Let N_M = The network accuracy of station "MCCOY", then

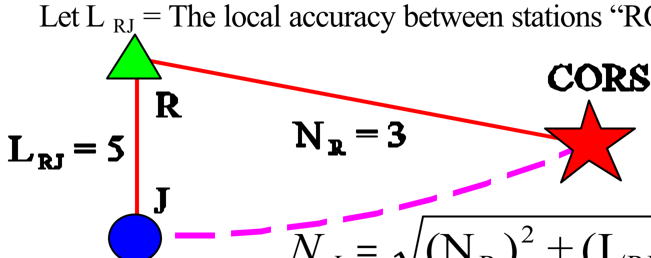


$$L_{HM} \approx \sqrt{(N_H)^2 + (N_M)^2} = \sqrt{(3)^2 + (4)^2} = 5$$

2) **NETWORK TIE MISSING:** If adjacent stations are well connected (e.g., property corners) with only one tie are made to existing control, the network accuracy for each station can be computed through the local accuracies to the network station.



TO COMPUTE NETWORK ACCURACY, N_J:
Let N_R = The network accuracy of station "ROMEO", and
Let L_{RJ} = The local accuracy between stations "ROMEO" and "JULIET", then



$$N_J = \sqrt{(N_R)^2 + (L_{RJ})^2} = \sqrt{(3)^2 + (5)^2} = 5.83$$

Table 2.1 Expected Local Accuracies (95%)

Positional Component	FBN/CBN	UDN	Height (2cm)	Height (5cm)
Horizontal Position	1 cm	various	1 cm	2 cm
Ellipsoidal Height	2 cm	various	2 cm	5 cm
Orthometric Height	3 cm	various	2 cm	5 cm

2.3 ELLIPSOIDAL AND ORTHOMETRIC HEIGHT ACCURACY RELATIONSHIPS

The use of GPS for vertical network surveys requires an understanding of the relationship between conventional and GPS height systems, and of problems unique to the vertical component of a GPS measurement.

Conventional trigonometric, spirit, or compensator leveling measures the relative elevations of points above an undulating equipotential surface called the geoid, which is close to, but not the same as, "mean sea level." An approximate example of a geoidal reference surface is NAVD 88. Elevations measured by conventional leveling are *Orthometric Heights.*

In contrast, GPS measures the relative elevations of points above a smooth, mathematically simple surface called an ellipsoid. An example of an ellipsoidal reference surface is GRS80, the defining surface for NAD 83. Elevations derived from GPS measurements are *Ellipsoidal Heights.*

The ellipsoidal (h) and orthometric (H) heights are closely related by the *Geoid Height* (N), the separation between the two reference surfaces, as shown in Figure 2.1 below. Geoid heights can be derived from GPS observations on bench marks, where both the ellipsoidal and orthometric heights have been measured for the same point. A network of GPS bench mark observations, gravity observations, and elevation models are used to develop a *geoid model*, from which geoid heights at other points in the area can be estimated. The accuracy of these geoid heights is dependant upon the accuracies of the various measurements used to construct the model.

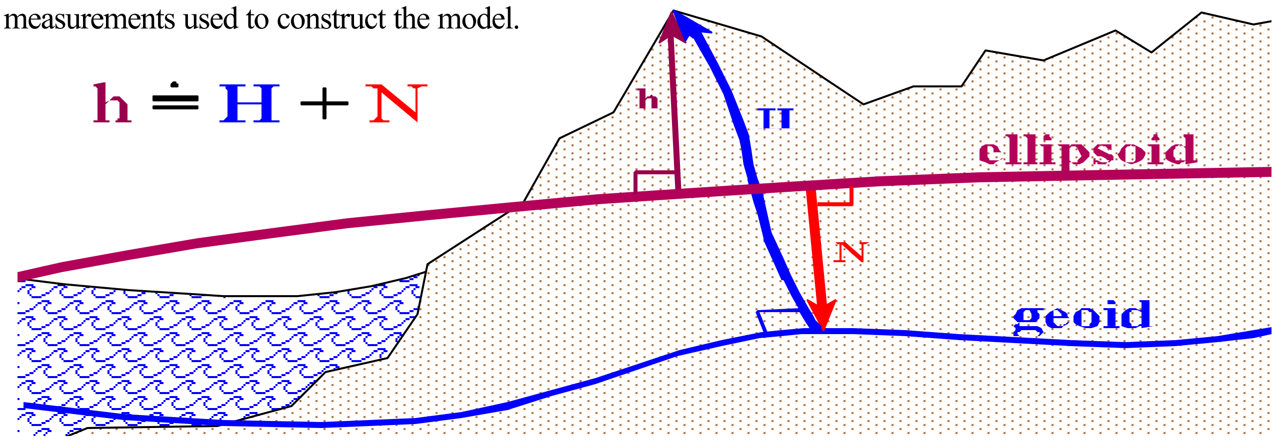


Figure 2.1 Relationship between ellipsoidal (h), orthometric (H), and geoid (N) heights.

The height equation h. H+N is only an approximation, as orthometric height is measured along a curved plumb line normal to the geoid surface, while the ellipsoidal and geoid heights are measured along straight lines normal to the ellipsoid surface. For land surveying applications, the height error associated with this approximation will always be **less than one centimeter**.

The height component of a GPS survey measurement is also affected by relatively poor geometric strength for trilateration, as the earth blocks all satellite signals from the hemisphere below the horizon. *This imbalance makes height measurements more susceptible than horizontal measurements to signal path errors from multipath or atmospheric conditions*. Accordingly, GPS height accuracies for a survey are typically **1½ - 3 times worse** than GPS horizontal accuracies, depending on data quality and base line length.

3. GENERAL GUIDELINES

3.1 NETWORK DESIGN

Survey should include all superior control stations in the vicinity, at least three or four.

3.2 SATELLITE GEOMETRY

HDOP and VDOP limits?
Sky blockage limits?

What to do during high DOP or blockage?

3.3 INSTRUMENTATION

Basic instrumentation for GPS network surveys includes multiple sets of receivers, antennas, fixed-height tripods, and meteorological instruments. Identical equipment should be used whenever possible to minimize equipment biases. The compatibility of mixing different instrument models or brands must be demonstrated by performing a validation survey (See Appendix 10.5).

GPS RECEIVER
The receivers used for network surveys should record the full-wavelength carrier phase and signal strength of both the L1 and L2 frequencies, and track at least eight satellites simultaneously on parallel channels. Dual-frequency instruments are required for all base lines longer than 1 km.

GPS ANTENNA
The antennas should have stable phase centers and choke rings or large ground planes to minimize multipath interference.

TRIPOD
The tripods must facilitate precise offset measurements between the mark datum point and the antenna reference point (ARP). Fixed-height tripods are preferable, due to the decreased potential for antenna centering and height measurement errors.

METEOROLOGICAL INSTRUMENTS
Portable weather instruments are used to determine temperature, relative humidity, and barometric pressure near the antenna phase center. Note that even though these data may not be used in the base line processing, they may be helpful during the analysis of the results and in future reprocessing with more robust software.

PERSONNEL
All field personnel should be trained in the avoidance of systematic errors during field operations. Field personnel often work alone and must be prepared to make wise, on-the-spot decisions regarding mark identification and stability, equipment use and troubleshooting, and antenna setup. Office personnel should be familiar with geodetic concepts and least squares adjustments.

Instrumentation guidelines are summarized in Table 5.1 below:

Table 5.1 Instrumentation Guidelines		**1 cm Horizontal 2 cm Vertical**	**2 cm Horizontal 5 cm Vertical**
GPS Receivers		Dual freq. required for base lines > 1 km	
GPS Antennas		Ground plane required; choke ring preferred	
Tripods & Tribrachs	Antenna 3-dimensional positioning tolerance Fixed-height tripod required	0.2 cm for all stations	0.4 cm for control & hub sta.
Thermometers	Temperature measurement tolerance	1 C	2 C
Hygrometers	Relative humidity measurement tolerance	2 %	4 %
Barometers	Barometric pressure measurement tolerance	1 mbar	2 mbar

3.4 CALIBRATION PROCEDURES

Survey equipment, like all scientific instrumentation, should be handled with care, maintained according to manufacturer specifications, and calibrated on a regular basis. An equipment calibration should be performed at the start and end of a project, before and after any maintenance, and at sufficient intervals to maintain data integrity. Any data not bracketed by successful calibrations are suspect. To prevent the invalidation of good data, frequent calibrations are recommended. The entire system of GPS equipment, personnel, and processing procedures should be proven with a validation survey as a final check to ensure all components interact properly. (See Appendix 10.5).

GPS ANTENNA

Antenna “calibration” measures the movements of the antenna phase center, the point measured in a GPS base line. For each antenna type, the phase center location varies with satellite elevation, azimuth, and signal frequency. When surveying over wide areas, or combining antenna types in a survey, such as with use of CORS, the relative phase center variations should be known and applied during processing. Intermittent use of detachable antenna accessories, such as ground planes and radomes, may also affect calibration characteristics and should be avoided.

Calibration guidelines are summarized in Table 6.1 below:

Table 6.1 Calibration Guidelines		Frequency
GPS Receivers	Firmware upgrades	When available
GPS Antennas	Antenna Calibration	Once per model
Tripods & Tribrachs	Check stability, plumb alignment, and height	Start and end of project
Thermometers	Comparison with an accurate standard	Start and end of project
Hygrometers	Comparison with an accurate standard	Start and end of project
Barometers	Comparison with an accurate standard	Start and end of project
Personnel	Retraining	Continuous

Are there realistic accuracy requirements for meteorological observations, considering that the data are not currently used in processing? More accurate readings require more expensive equipment.

3.5 FIELD PROCEDURES

Upon arrival at a station, the monument should be inspected to ensure stability and proper identification. A pencil rubbing, sketch, or photograph of the mark shall be taken for the field records. Satellite signal obstructions and potential multipath or interference sources should be described on the field log or on a visibility obstruction diagram. The accuracy of the station description should be checked and updated as necessary.

Proper antenna setup is critical to survey accuracy. The antenna must be carefully plumbed and stabilized, and verified plumb at the beginning and end of each observation session. Level bubbles shall be shaded for at least 3 minutes before each use to minimize convective currents in the bubble fluid. The reference arrow on all antennas should be oriented to true north. When practical, photographs detailing the antenna setup shall be taken for the field records.

When a fixed-height tripod is not used, the height of the antenna above the mark must be carefully measured. Totally independent measurements of the antenna height in both metric and imperial units shall be made before and after each observation. All antenna height measurement computations must be checked and initialed by an independent observer. Low tripod setups should be employed whenever practical to minimize setup eccentricities; however, the antenna shall be positioned high enough to avoid signal obstructions.

Meteorological observations shall be recorded at the beginning and end of a session, at regular 2 to 3 hour intervals during extended sessions, and at sufficiently smaller intervals during weather events to describe all conditions experienced. Weather measurements shall be observed **at or near the antenna phase center, but above any ground effect**. The instruments should be allowed ample time (approximately 10 minutes before weather observations) to stabilize to ambient conditions.

Detailed field records must be kept for each observing session. At a minimum, field logs should identify the following information:

- Observer name & contact information
- Station designation and other IDs
- Equipment identification information *
- Antenna height measurements
- Weather observations
- Observer notes

* ALL instrumentation shall be traceable from logged information. The complete model, part numbers, and serial numbers of the receivers, antennas, tripods, and tribrachs shall be noted on field records. Sample NGS field logs are provided in Appendix 10.2.

Why record meteorology at antenna height? Is there really a great difference in temp, pressure, or humidity between chest-height and 2.0 meters? Because the GPS signal is affected along its entire course through the atmosphere, why is it important to concentrate on conditions at one discrete point?

3.6 OFFICE PROCEDURES

A. DATA QUALITY CONTROL

All field records should be examined carefully and all field calculations checked for errors. The pencil rubbings should be inspected to ensure agreement with the station descriptions. Antenna height measurement computations should be rigorously examined.

The status of the GPS satellite constellation and ionospheric activity should be monitored. See Appendix 10.3 for information sources.

B. BASE LINE PROCESSING

All base line processing shall be accomplished using NGS-developed PAGES software, or other interactive, graphics producing software which produces results equivalent to PAGES.

Use precise ephemerides. See Appendix 10.3 for ephemerides sources.

For sessions of 30 minutes or more, process data using 30-second epochs and 15-degree elevation masks. For sessions less than 30 minutes, process data using 5-second epochs and 15-degree elevation masks. **Note that the use of shorter epochs may improve ease of data processing.**

A model to account for tropospheric effects must be used. Measured meteorological data should be used only when it has been determined that the **instruments have been properly calibrated** and the measurements accurately represent the **current** atmospheric conditions at the station. If **standard meteorological data** are used instead of actual measured values, the processing software must account for changes in standard default values due to the station's location and height above the vertical datum. For base lines greater than 15 kilometers or with **"large"** height differences, a relative tropospheric scale parameter should be solved for, along with the base line vector components.

Final processing shall consist of **fixing all integers** for each base line. For base lines less than 10 km, the L1 fixed solution may be the best choice. For base lines greater than **40 km**, a session may consist of a set of partially fixed integers and may also include float solutions where no integers could be fixed.

C. DATA ADJUSTMENT AND ANALYSIS

The quality of acquired data shall be determined from the double-difference residual plots and RMSE values. Final coordinates and their quality assessment shall be determined by least squares adjustment, analysis of repeated base lines, and free adjustment residuals.

The RMSE values for each computed base line (adjacent station pairs) must not exceed **1.5 cm.** Adjustments must evaluate independent (non-trivial) base lines only, to avoid misstating the network degrees of freedom. All observations shall be properly weighted.

Describe how orthometric heights are computed. How is the geoid model used?

D. REOBSERVATION CRITERIA

A repetition of observations is required if the difference in horizontal position or ellipsoidal height between the repeat observations exceeds the limits shown in Table 8.1.

E. DOCUMENTATION

A project report shall be written to describe the objectives, methods, and results of the survey. The report must be signed by person of responsible charge. Field records and data files should be archived for possible future analysis. Data formats acceptable for submission to NGS for inclusion in the NSRS are described in Appendix 10.4.

Office procedures are summarized in Table 8.1 below:

Table 3.6 Office Procedure Guidelines:	**1 cm Horizontal 2 cm Vertical**	**2 cm Horizontal 5 cm Vertical**
ADJUSTMENT ANALYSIS CRITERIA:		
Maximum variance of unit weight (1.0 ideal)	1.5	1.5
Minimum degrees of freedom per station	2 degrees of freedom	1 degree of freedom
Standard deviation of observation residuals, cm	.01 cm	0.1 cm
Standard error of base line components, cm	.01 cm	0.1 cm
Standardized residuals - pass chi-square test	yes	yes
- pass tau criterion	yes	yes
Maximum % observations rejected	10%	10%

4. DETAILED GUIDELINES

4.1 SINGLE RECEIVER, MODEL AIDED

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.1.1 NETWORK AND SATELLITE GEOMETRY

4.1.2 INSTRUMENTATION

4.1.3 CALIBRATION PROCEDURES

4.1.4 FIELD PROCEDURES

4.1.5 OFFICE PROCEDURES

4.1.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.2 SINGLE RECEIVER, DATA AIDED

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.2.1 NETWORK AND SATELLITE GEOMETRY

4.2.2 INSTRUMENTATION

4.2.3 CALIBRATION PROCEDURES

4.2.4 FIELD PROCEDURES

4.2.5 OFFICE PROCEDURES

4.2.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.3 DIFFERENTIAL

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.3.1 NETWORK AND SATELLITE GEOMETRY

4.3.2 INSTRUMENTATION

4.3.3 CALIBRATION PROCEDURES

4.3.4 FIELD PROCEDURES

4.3.5 OFFICE PROCEDURES

4.3.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.4 STATIC

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.4.1 NETWORK AND SATELLITE GEOMETRY

4.4.2 INSTRUMENTATION

4.4.3 CALIBRATION PROCEDURES

4.4.4 FIELD PROCEDURES

4.4.5 OFFICE PROCEDURES

4.4.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.5 RAPID-STATIC

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.5.1 NETWORK AND SATELLITE GEOMETRY

4.5.2 INSTRUMENTATION

4.5.3 CALIBRATION PROCEDURES

4.5.4 FIELD PROCEDURES

4.5.5 OFFICE PROCEDURES

4.5.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.6 POST-PROCESSED KINEMATIC

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.6.1 NETWORK AND SATELLITE GEOMETRY

4.6.2 INSTRUMENTATION

4.6.3 CALIBRATION PROCEDURES

4.6.4 FIELD PROCEDURES

4.6.5 OFFICE PROCEDURES

4.6.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.7 REAL-TIME KINEMATIC

This type of GPS technique is characterized by . . . See also Section 3, General Guidelines.

4.7.1 NETWORK AND SATELLITE GEOMETRY

4.7.2 INSTRUMENTATION

4.7.3 CALIBRATION PROCEDURES

4.7.4 FIELD PROCEDURES

4.7.5 OFFICE PROCEDURES

4.7.6 SAMPLE PROJECT AND OBSERVING SCHEME

4.8 FEDERAL & COMMUNITY BASE NETWORK SURVEYS

Federal and Community Base Networks (FBN/CBN) are statewide GPS survey networks which form the highest order of monumented control for the NSRS. Comprised of an NGS-maintained Federal Base Network at 100 km station spacing and a volunteer-densified Cooperative Base Network at 25-50 km spacing, FBN/CBN stations serve as control for regional and local surveys. Contemporary FBN/CBN surveys are conducted in accordance with the following specifications:

Station Requirements:

- **FBN/CBN Stations**: The survey shall include FBN stations established at 100 km nominal spacing and additional CBN stations if desired. Refer to "FBN Station Selection Guidelines"$_4$ for FBN/CBN monumentation and siting criteria.

- **Hub Stations**: The survey shall include at least one hub station located within 300 km of each FBN/CBN station. Hub stations should include all National CORS in the project area, and any bench mark or FBN/CBN stations located in secure areas.

- **Bench Marks**: The survey shall include at least one each, **first- or second-order, stability class -A or class-B** bench mark located within 200 km of each FBN/CBN station.

Observation Requirements:

- **FBN/CBN Stations**: All FBN/CBN stations shall be observed in at least three sessions on 3 different days. Each observation shall be continuous for at least 5 ½ hours, and simultaneous with all other stations in the observing session. At least one of the three sessions shall be observed under a unique satellite configuration, offset **4 or more** sidereal hours from other observations. Session times shall be selected to minimize Positional Dilution of Precision (PDOP) throughout the observation.

  Each FBN/CBN station shall be co-observed with a hub station and adjacent stations. At least half of the station pair (base line) observations shall be repeated. Data shall be recorded at 15 second epochs and 10 degree elevation masks.

- **Hub Stations**: Each hub station shall be observed with the nearest National CORS station for one session of at least 72 continuous hours with 30 second epochs.

These guidelines for FBN/CBN surveys are summarized in Table 4.1 below:

Table 4.1 Network Design Guidelines for FBN/CBN Surveys

Minimum Number of Stations	All National CORS in or near the project area
Maximum Station Spacing	Between FBN/CBN stations # 100 km (nominal spacing) Between FBN/CBN and hub stations # 300 km Between FBN/CBN and bench marks # 200 km
Required Base lines	For FBN/CBN stations: To a hub station in each session, To each adjacent station Repeat at least 50% of all base lines For hub stations: To the nearest National CORS
Observations per Base line	For FBN/CBN stations, $ 3 each, 5½ hour observations on 3 different days For hub stations, $ 1 each, 72 hour observation, 30 second epochs
Sidereal Time Offset Between Repeated Observations	Repeated observations are conducted on different days, At least one observation shall be offset by ± 4 hours
Fixed-height Tripods Required?	Required for all FBN stations, hub stations, and bench marks
Acquire Meteorological Data?	At all stations at the beginning, middle, and end of each observation
Data Acquisition Parameters	15 second epochs, 10 degree elevation masks
Data Processing Parameters	30 second epochs, 15 degree elevation masks, precise ephemerides

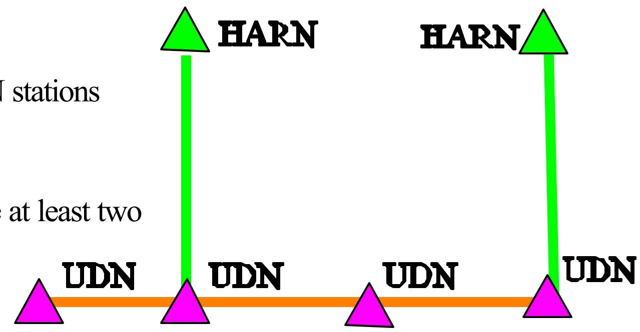
---

NOTE: The term “HUB” is used differently in PAGES processing.

4.9 USER DENSIFICATION NETWORK SURVEYS

User Densification Network (UDN) surveys are used for regional densification of the FBN/CBN networks. UDN surveys are conducted in accordance with the following specifications:

Station Requirements:



- **UDN Stations**: The survey shall include UDN stations established at 25 km spacing or less.

- **FBN/CBN Stations**: The survey shall include at least two FBN/CBN stations.

Observation Requirements:

- **UDN Stations**: Each UDN station shall be observed in at least two 30 minute sessions. Each UDN station shall be co-observed with adjacent stations. Data shall be recorded at 15 second epochs and 10 degree elevation masks.

These guidelines for UDN surveys are summarized in Table 4.2 below:

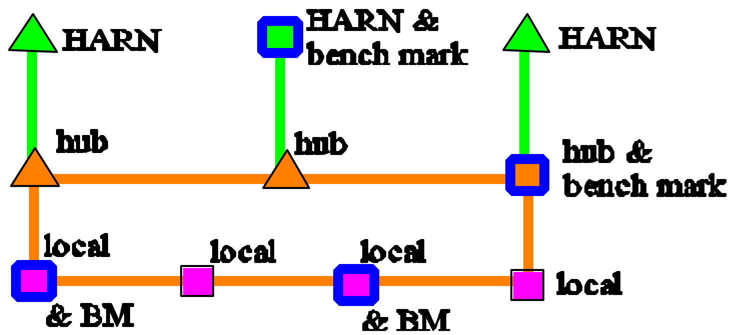
Table 4.2 Network Design Guidelines for UDN Surveys

Minimum Number of Stations	At least two FBN/CBN stations
Maximum Station Spacing	# 25 km between UDN stations
Required Base lines	To adjacent stations
Observations per Base line	$ 2 each, 30 minute observations
Sidereal Time Offset Between Repeated Observations	No time offset required
Fixed-height Tripods Required?	No fixed-height tripods required
Acquire Meteorological Data?	At representative stations in the middle of each observation
Data Acquisition Parameters	30 second epochs, 15 degree elevation masks
Data Processing Parameters	30 second epochs, 15 degree elevation masks, precise or rapid ephemerides

4.10 GPS ORTHOMETRIC HEIGHT SURVEYS

Recent studies have shown that with sufficient orthometric height control, high accuracy vertical control projects can be efficiently performed using GPS. Orthometric height surveys are conducted in accordance with the following specifications:

Station Requirements:



- **Local Stations**: The height stations established in this survey are referred to as local stations. See Table 4.3 for maximum station spacings.

- **Control Stations**: The survey shall include three or more primary control stations distributed throughout the project area. All control stations shall be National CORS or vertical first-order, stability class-A or class-B FBN/CBN stations.

- **Hub Stations**: The survey shall include three or more subordinate control stations, called hub stations, distributed throughout the project and located within 75 km of the control stations. See Table 4.3 for maximum station spacings. Although hub stations can be newly established in this project, the use of existing FBN/CBN stations and stable bench marks is preferred.

- **Bench marks**: The survey shall include at least four each, vertical first-order, stability class-A or class-B bench marks spaced less than 20 km apart and distributed both horizontally and vertically throughout the project area. Use additional bench marks whenever practical.

Observation Requirements:

- **Local Stations**: All local stations shall be connected to the two nearest adjacent stations of any type by observing for 30 minutes on each of 2 or more days, at different times of day, and shall be connected to two hub or control stations by independent paths. For these observations, please note the following exceptions:

  - For base lines longer than 10 km, increase the 30 minute observations to 1 hour.
  - For base lines longer than 15 km, increase the 30 minute observations to 2 hours.
  - For the 2 cm horizontal, 5 cm orthometric height local accuracy level, there is no minimum time requirement. The base lines shall be observed long enough to ensure that all integers are fixed and the Root Mean Square Error (RMSE) for the base line solution does not exceed 1.5 cm.

- **Hub Stations**: Each hub station shall be directly connected to the nearest control station and two other hub stations, and shall be connected to a second control station by an independent path. Each of these base lines shall be observed for 5 hours on each of 3 or more days. Hub stations shall be connected to the two nearest hub stations, and the two nearest adjacent stations of any type, by observing for at least 30 minutes on each of 2 or more days, at different times of day.

Independence of Observations:

In an attempt to provide independent atmospheric, satellite, and tidal conditions, subsequent observations of all repeated base lines shall occur on different days, with as long a time interval between observations as is practical. Because the GPS satellite geometry repeats every 12 hours*, an additional time shift of ± 3 to 9 hours is required to observe unique satellite constellations. Refer to the following table for examples:

First Session	Repeated Session (a.m. or p.m.)	First Session	Repeated Session (a.m. or p.m.)
Began at 1	Observe between 4 and 10	Began at 7	Observe between 10 and 4
Began at 2	Observe between 5 and 11	Began at 8	Observe between 11 and 5
Began at 3	Observe between 6 and 12	Began at 9	Observe between 12 and 6
Began at 4	Observe between 7 and 1	Began at 10	Observe between 1 and 7
Began at 5	Observe between 8 and 2	Began at 11	Observe between 2 and 8
Began at 6	Observe between 9 and 3	Began at 12	Observe between 3 and 9

* Note that the actual orbit period is approximately 11 hours and 58 minutes, precessing 4 minutes per day. For repeated base lines observed more than 1 week apart, this daily 4-minute change should be taken into account when scheduling the repeated sessions to meet the satellite geometry requirement.

These guidelines for GPS orthometric height surveys are summarized in Table 4.3 below:

Table 4.3 Network Design Guidelines for GPS Orthometric Height Surveys

Station Type:	Control Stations		Hub Stations		Local Stations	
Local Accuracy:	1 cm Horizontal 2 cm Orthometric	2 cm Horizontal 5 cm Orthometric	1 cm Horizontal 2 cm Orthometric	2 cm Horizontal 5 cm Orthometric	1 cm Horizontal 2 cm Orthometric	2 cm Horizontal 5 cm Orthometric
Min. # stations	3 or more control stations		3 or more hub stations		No minimum number	
Max. Station Spacing	Between control and hub stations # 75 km spacing		40 km spacing	50 km spacing	10 km spacing, average # 7 km	20 km spacing, average # 10 km
Required Base line Ties	Control stations must be CORS or existing A- or B- order NSRS stations with 3-D ITRF coordinates.		5 hour observations: To nearest control, two other hub stations, and independent path to second control. 30 minute obs: To two nearest hub stations and two nearest adjacent stations.		Independent paths to two hub or control stations; To two nearest adjacent stations.	
Observations per Base line [1]	5 hour observations on 3 days		5 hour observations on 3 days 30 minute observations on 2 days		30 minute obs. on 2 days	No minimum time obs. on 2 days
Sidereal Time Between Obs.	Repeat observations on different days, ± 3 to 9 hours		Repeat observations on different days, ± 3 to 9 hours		Repeat observations on different days, ± 3 to 9 hours	
Fixed Height Tripod Rqd.	Yes		Yes	No	Yes	No
Acquire Met. Data	At the beginning, middle, and end of session		At the beginning and end of session		No	
Data Acq. Parameters	15 seconds, 10 degrees VDOP < 6 for 90% of session		15 seconds, 10 degrees VDOP < 6 for 90% of session		15 sec,10 degree VDOP<6 for 90%	5 sec, 10 degree VDOP<6 for 100%
Data Proc. Parameters	30 seconds, 15 degrees precise ephemerides		30 seconds, 15 degrees precise ephemerides		30 sec, 5 degree precise ephemeris	5 sec, 15 degree precise ephemeris

1. For base lines longer than 10 km, increase the 30 minute observations to 1 hour. For base lines longer than 15 km, increase the 30 minute observations to 2 hours. While there is no minimum observation time for the 2 cm horizontal, 5 cm orthometric height local accuracy observations at local stations, each base line shall be observed long enough in each session to ensure that all integers are fixed and the RMSE for the base line solution does not exceed 1.5 cm.

10. APPENDICES

10.1 DEFINITIONS

Define any acronyms and technical terms used, if necessary

10.2 SAMPLE PROJECT AND OBSERVING SCHEME

Illustrations showing project base lines, similar to NGS-58
Sample field logs

10.3 AVAILABILITY OF GEODETIC INFORMATION

10.3.1 DATASHEETS

10.3.2 CORS DATA AND EPHEMERIDES

10.4 PROCEDURES FOR SUBMITTING DATA TO NGS

10.5 VALIDATION SURVEYS

11. REFERENCES

1. August 1, 1989 FGCC (Hull)
   DRAFT Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques, Version 5.0, Reprinted with corrections
2. November 1997 NOAA Technical Memorandum NOS NGS-58 (Zilkoski et al.)
   Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 CM and 5 CM)
3. 1998 FGDC
   Geospatial Positioning Accuracy Standards, Parts 1 and 2
4. May 08, 1996 NGS
   FBN Station Selection Guidelines
5. September 1984 FGCC (Bossler)
   Standards and Specifications for Geodetic Control Networks.

Other Specifications:
May 23, 1995, FGCS (Lapine)
DRAFT Standards for Geodetic Control Networks.
December 1992, Geomatics Canada
Guidelines and Specifications for GPS Surveys, Release 2.1
September 1996, Geomatics Canada
Accuracy Standards for Positioning, Version 1.0
July 1993, Geomatics Canada
GPS Positioning Guide. (C. Erickson.)
November 1993, Canadian Hydrographic Service
Procedures and Specifications for GPS Surveying, A GPS Handbook.

Other Federal Guidelines:	DMA, USACE, BLM
State Guidelines:	California, Missouri, Wisconsin

9. GPS ACCURACY: OCCUPATION TIME / BASE LINE DISTANCE

Section pending.

```
Use data from Dave Zilkoski’s studies and Mark Eckl’s CORS
Length-Time-Accuracy reports to justify the guidelines and
demonstrate accuracies achievable from these guidelines. Provide
references for all accuracies claimed in Table 2.1 above. NOTE:
Because Eckl’s project uses CORS data and PAGES software only,
it will not show errors attributable to instrument setup errors
or other processing software.
```